ULTRASOUND – THE FIRST FIFTY YEARS

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I. INTRODUCTION

The application of x-rays to medicine has a historical perspective that is quite unlike any other medical technology. The step change that arose from the discovery of X-rays by Röntgen, announced in January 1896, and in its immediate application by medical doctors for clinical diagnosis, was highly unusual. The time-line for ultrasound is closer to the more common, slower ingress of a technology into clinical medicine. A new phenomenon, infrared or ultraviolet radiation for example, is first discovered and its properties explored in academic laboratories of physics, where a greater understanding is developed. In due course, typically as a result of a medical doctor working in partnership with an engineer or scientist, clinical applications are explored. The first serious investigation of ultrasound occurred at the end of the extraordinary final decade of the nineteenth century, which also saw the discovery of x-rays, radio waves and radioactivity, and the first use of ultraviolet waves and of high frequency currents for medical applications [1]. It would be nearly half a century before ultrasound started to emerge clinically as a potential therapeutic agent, followed shortly by its development for diagnosis and imaging.

In this article I shall trace the most important milestones during these fifty years, as ultrasonic technologies were developed for other purposes before they started to be explored for medical applications, and as the effects on living organisms were investigated, so giving a basis for the development of ultrasonic therapies and also a framework for the safe exploitation of ultrasound for medical diagnosis.

II. AIR-BORNE ULTRASOUND

Physiological acoustics, the investigation of hearing, was an area of active investigation during the nineteenth century, a discipline within which 'Sensations of Tone' by the physiologist and physicist, Hermann Helmholtz, first published in 1862, was the dominant text. It was well appreciated that the ear was limited in the range of frequencies to which it could respond, and there were several early attempts to measure the upper limit, notably by physicist César Depretz in Paris and by the English-born psychologist William Preyer working in Germany [2,3]. There was little quantitative agreement on the upper limit to human hearing, however, the reported age-dependent threshold between audible and ultrasonic frequencies lying between about 16 kHz and 40 kHz [4].

Rudolph Koenig's publication in 1899 marks the first serious exploration of ultrasonic waves in air [5]. Koenig demonstrated that ultrasonic waves up to 90 kHz could be generated using a series of small tuning forks and steel bars only a few millimeters long. However, they were not loud enough for audiological testing and Max Edelmann then used an improved Galton whistle to generate louder ultrasonic frequencies up to 110 kHz [6,7]. Eventually, using a series of careful measurements, Franz Schultze confirmed Preyer's estimate of 20 kHz as a reasonable upper threshold for human hearing, so setting the lower limit of the ultrasonic spectrum that remains generally accepted today [8].

Wilhelm Altberg (1877-1942) was born in Belarus, completing his schooling in Smolsensk. After graduation from Moscow University he continued working there under the guidance of the physicist Pyotr Lebedev, carrying out two key experiments in the history of ultrasound. Lebedev had been the first to demonstrate, in 1899, the existence of radiation pressure in an electromagnetic wave, as predicted by Clerk Maxwell. In 1903, the year after Lord Rayleigh's analysis of the relationship between energy density and radiation pressure in acoustic and electromagnetic waves [9], Altberg was the first to use radiation pressure to measure the intensity of a sound wave [10,11]. This work marks the first occasion in this story when a key experiment is directly relevant to later developments in the physics of medical ultrasound. Radiation force is now the primary means to measure acoustic power in beams used for therapeutic and diagnostic applications of ultrasound, and details are given elsewhere in this history. It also forms the basis of radiation force elastography [12].

In 1907, Altberg secured his place in the history of ultrasound by his discovery that the 'singing arc', described by William Duddell [13], could also emit acoustic waves at ultrasonic frequencies [14]. In his delightful acoustic experiment, he investigated the spectrum of the pulsed acoustic waves generated by a spark discharge, using a diffraction grating made from glass rods. He measured the diffraction patterns using the radiation force exerted on a 4x12 mm mica vane suspended in a draft-proof box by a quartz thread, observing its displacement by the radiation force. From the angle of the main diffraction lobe he concluded that he was able to generate wavelengths as small as 1 mm, in other words, frequencies in air of a little over 300 kHz. One further observation completes this preliminary overview. In 1911, Lebedev and his student Neklepajev explained why Altberg had been unable to detect wavelengths shorter than 1 mm. It resulted from their absorption, for which the coefficient is dependent on the square of the frequency, so placing a limit on the useful penetration of higher ultrasonic frequencies through air [15,16]. Altberg eventually settled in Petrograd (later Leningrad) where he died during the siege in 1942 [17].

III. Ultrasound for submarine detection

The frequency-dependent absorption of ultrasonic waves in air served to limit the initial interest in the use of acoustic radiation above the audible limit, initially relegating the phenomenon to no more than a scientific curiosity. Then two men, one in Britain and the second a Russian émigré working in Austria, recognized that ultrasound had the potential to resolve a practical problem, that of underwater location.

The first documented proposal that ultrasound could be used for underwater detection was made in 1912 by Lewis Fry Richardson (1881-1953). He was born in Newcastle-upon-Tyne, England, into a prosperous Quaker family. A decade after graduation from Cambridge University, he was facing redundancy from the Sunbeam Lamp Company as it faced bankruptcy. It was at this moment that he made his single contribution to the history of ultrasound. On 15th April 1912, the Titanic collided with an iceberg south of Newfoundland and sank with a huge loss of life. He immediately submitted two patent applications in quick succession to the British Patent Office [18,19], the second proposing an underwater ultrasonic system instead of the airborne system of the first. The purpose of the apparatus was to warn a ship of its nearness to an object ahead. Whilst the provisional specification, filed on 10th May 1912, stated that the best frequency 'will probably be of the order of 100,000 complete vibrations per second', the complete specification, filed on 10 December, abandoned his idea of using ultrasound, setting the operating frequency to be '4780 or more complete vibrations per second'. Resetting the frequency into the audio range altered his approach to directionality, now achieved using a rectangular aperture, creating a fan beam to avoid reflections from the seabed. There is no evidence that any instrument was ever constructed. Indeed, this episode in Richardson's life is considered so unimportant in his career that the two patents are not even included among the 127 publications listed in his biography [20].

It was left to the impetus from submarine warfare to cause the development of the first operational ultrasound pulse-echo location system. Details of these developments have been drawn from several sources [21,22,23].

The sinking of three British cruisers in September 1914 by submarine-launched torpedoes served to emphasize the huge threat they posed to Allied shipping. A young Russian electrical engineer, Constantin Chilowsky, was convalescing from tuberculosis in a Swiss mountain hotel in 1915 when he developed his plan for an ultrasonic system for submarine detection. He had been politically active in Moscow and his family had helped him to escape to Switzerland. His proposal was to use a magnetically-driven diaphragm as a source of ultrasound instead of the underwater whistle suggested by Richardson.

His proposal passed over several academic and diplomatic desks before Paul Painlevé, Minister of Public Education and Inventions, passed it on to Paul Langevin (1872-1946) in February 1915. The renowned French physicist, pacifist by inclination, had been initially unwilling to be drawn into war activities, but he had been encouraged by his past student, Maurice de Broglie, who was working for the navy on radio communications, to find a way to detect enemy submarines.

During the next two years, Langevin's team slowly developed a working pulse-echo system in his laboratory in the *École municipal de physique et chemie industrielles*, and at the French naval base at Toulon. They replaced Chilowski's loudspeaker with a 'singing condenser' as transmitter. They drew on electronic techniques designed for wireless telegraphy for the French navy, and one of the designers, Capitaine de Frégate Colin, was loaned to the project. The condenser transmitter is shown in Figure 1. It consisted of a circular metal plate, insulated by a thick coating of resin, on which a sheet of mica was held under a vacuum using a Gaede rotary vacuum pump, and was free to vibrate. Sea-water formed the other electrode. By July 1915, the team was able to generate ultrasonic intensities around 100 mW cm^{-2} measured using radiation force. They were unable to make the transducer work as a receiver, and designed a special carbon granule hydrophone, based on well-established carbon microphone technology for audio frequencies. By April 1916, they filed a patent on this system [24] shortly before Chilowsky and Langevin parted company.

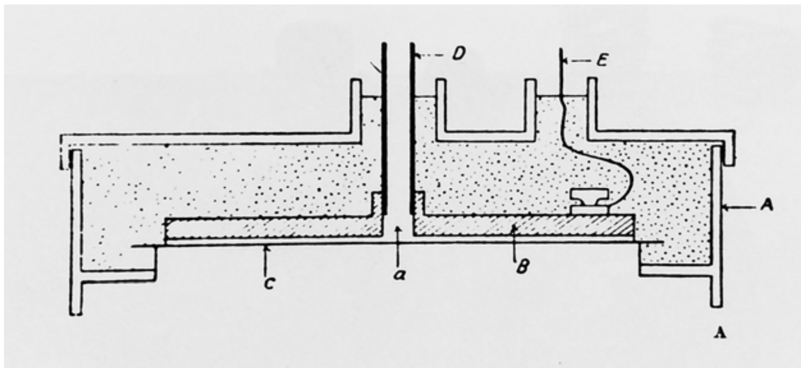

Fig 1. Langevin's singing condenser transducer c. 1916, consisting of a circular metal disc (B), mica sheet (C), vacuum tube (D) and box (A) filled with insulating compound.

On 17 Feb 1917, when Maurice de Broglie visited London to present Langevin's report to the British Board of Inventions and Research (BIR) he declared that the methods described

'represent the result of two years' continuous work, during which other methods have been tried over and over again without success. Though it is probable that they may be eventually improved, it appears certain that time will be saved by not departing (for the present) from the constructional details hereafter described. ' [25]

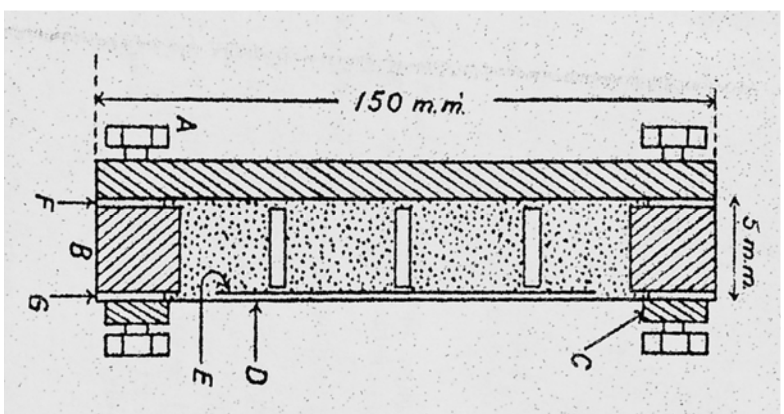

Fig 2. Experimental large area carbon hydrophone. Langevin 1917. The carbon granules are packed in water between a brass disc A and a sheet of mica D, clamped onto an ebony ring B. A steel plate E is cemented inside the mica. Glass panels prevent the carbon becoming too tightly packed.

The capacitor transmitter emitted 50 ms pulses of 100 MHz ultrasound, at a rate of 2 Hz. The carbon microphone was placed at the focus of a parabolic mirror, 120 cm diameter, to receive the echoes. The envelope of the received signal was demodulated and detected audibly, valve amplifiers being used at both the high frequency and audio stages to increase sensitivity. Nevertheless, they had been unable to build robust transducers with reproducible characteristics. Sparking could not be excluded and each new transmitter had 'but an extremely short life' [26]. The sensitivity of the carbon microphone was found to alter with depth and movement of the sea and a new large-area carbon hydrophone, 15 cm diameter, was under development that it was hoped would be more stable (Figure 2). So, while the potential of ultrasound as a means for undersea detection and communication was by then established, a reliable means to generate and receive ultrasound signals of sufficient strength still remained elusive.

By the time of de Broglie's visit, Britain had been operating its own research programme for about 6 months. Ernest Rutherford was a member of the BIR advisory panel for submarines and wireless telegraphy. At this stage, the preferred option for submarine detection was to use hydrophones to detect audible sounds emitted by the submarine and, indeed, this remained the preferred option throughout the war. Two other panel members, Richard Paget and William Duddell had visited France in June 1916 to learn more about the work of Langevin's team, returning to encourage Rutherford to investigate the use of ultrasound. As a result, in August, the Canadian physicist Robert Boyle (1883-1955) who was already working for the BIR in Manchester, was placed in charge of a new project to investigate underwater ultrasound, assigned the task to reproduce and test the Chilowsky/Langevin system.

A. Quartz ultrasound transducers

Once appointed to the ultrasound project, Boyle worked initially in Duddell's testing laboratory in South Acton, London, eventually moving to the Admiralty Research station at Parkeston Quay, Harwich. During the latter months of 1916, assisted by S G Brown FRS, Boyle did his best with limited resources to verify and develop some of the French results. They concentrated on the design of carbon hydrophones for reception and needed a calibrated source to test sensitivity. They had previously rejected quartz as a primary hydrophone material and also as a replacement for the French capacitative transmitter, but were considering it as a test source for hydrophone response.

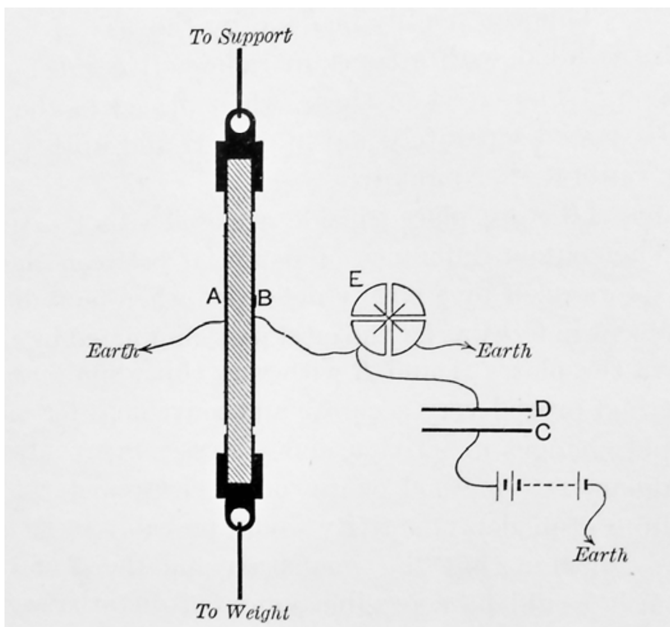

Fig 3. The quartz piézo-électrique for measurement of ionization. Piezoelectric charge across the quartz AB is balanced against the capacitor charge CD using the electrometer E, radioactivity measured by the discharge time for a fixed weight. Rutherford *Radioactivity* (1904).

On 12 December, Boyle wrote to Rutherford, 'We have done what we could to get some measurement of the minimum amplitude able to affect our high frequency detection hydrophones, using your quartz piézo-électrique to give us small measureable(?) amplitudes' [27]. The 'quartz piézo-électrique' was a slice of quartz cut perpendicularly to the electric axis, widely used in Rutherford's laboratory for the measurement of radioactivity by transducing charge from ionization into force, measured by weighing. (Figure 3). This method had been created by Jacques Curie, and used by Marie and Pierre Curie to quantify the radioactivity of radium some twenty years before.

Almost immediately after de Broglie had told the British team that the French design was complete, Langevin finally realized the key to exploiting quartz for transmission. Langevin had worked as a PhD student under Pierre Curie, and so understood the difference between the X-cut quartz, used by the

Curie brothers in their investigations of piezoelectricity in 1880, and the slice orientation used in the quartz piézo-électrique. In his own words 'I thought (February 1917) of utilizing the piezoelectric properties of quartz, first of all for receiving.' adding, significantly 'Instead of the deposition of it made by Pierre Curie in his apparatus for electrostatic measurements …. I thought it preferable to make use of the compression of the quartz in the same direction as its electrical axis, instead of by traction in a direction perpendicular to the electrical and optical axes. ' [21]

The first step was to replace the large-area carbon microphone with a quartz plate. Langevin obtained a quartz crystal of sufficient purity and volume from Ivan Werlein, an established Paris supplier of optical instruments. He persuaded Werlein to cut slices, 10 cm x 10 cm, from a 25 cm quartz crystal showpiece in his shop window. His first quartz receivers were 'composed of a thin sheet (of) quartz [or several plates in juxtaposition], placed perpendicularly to an electrical axis, and in contact with the water on one side (either directly, or by the medium of a thin protective sheet attached, mica for example); and on the other side with an insulated metallic plate forming the internal armature of a condenser in which the quartz formed the dielectric, and the salt-water the external armature, this condenser forming part of an attuned oscillating circuit.'

The received 100 kHz signal was connected to a tuned multi-stage triode amplifier which had just become available as part of a separate French research programme by the *Radiotelegraphie militaire*. The first results immediately showed promise and, at the end of March, Langevin visited London to discuss further collaboration between the two groups. The subsequent close working relationship was undoubtedly facilitated by Langevin's fluency in English, and Boyle's competence in French, having spent many years in French-speaking Montreal. At the beginning of May a joint Anglo-French mission set off to the USA to discuss co-operative working to support the Allied war efforts. This initiated several programmes of new work in the USA, notably at the New London Naval Experimental Station, at Columbia University, at the General Electric Company and at Weslyan University, the home base of Walter G Cady [23].

Fig 4. Members of the French and British teams for ultrasonic submarine detection. Summer 1917, Toulon dockyard. L to R. Capitaine de Frégate Colin, Lt R Saville, Robert Boyle, Paul Langevin, Marcel Tournier.

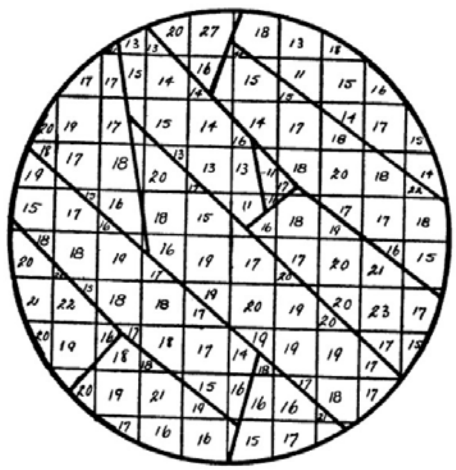

Fig 5. A quartz mosaic marked with the relative sensitivities of each element. (Boyle, [31])

When Boyle arrived in Paris on 23 May, accompanied by Lieut R Saville RNVR, he found Langevin 'about to try a quartz, piezo-electric transmitter' [28]. They visited Langevin's laboratories and the workshop where the quartz plates were being cut, tested and mounted. They then continued to the Arsenal at Toulon where they took part in the experiments there (Figure 4). By then, the French team had entirely replaced the carbon receivers with quartz, but were still working with both condenser and quartz transmitters at frequencies up to 100 kHz. The quartz was being driven at resonance by two 50 W valves in parallel, pulsed to evaluate pulse-echo detection, and continuously for underwater communications. By the time Boyle returned to England at the end of July he could report very strong one-way transmission over 500 m, with a practical limit of sensitivity of about 1000 m, attributed to refraction rather than absorption.

The limited supply of large quartz crystals led to the use of a mosaic of smaller thinner crystals. This brought its own challenges, as the cut slices had to be selected and polished to ensure uniformity of response across the whole transducer (Figure 5). By bonding the quartz to a steel substrate, ultrasonic resonance could be achieved without resorting to thick quartz plates and, for a given dimensional change, a lower driving voltage could be used.

Both the French and British teams would use these principles as their designs developed. Beyond these, their designs diverged. The French solution was Langevin's quartz sandwich transducer [29] (Figure 6). A 20 cm square mosaic of quartz plates about 4 mm thick was bonded using insulting cement between two plates of steel, each 3 cm thick, the whole sandwich air-backed. The freedom to build a transducer with a wider aperture was exploited, allowing the operating frequency to be lowered to 40 kHz.

Boyle recognized the need to move fast, even if this meant compromising design. He therefore decided against Langevin's air-backed resonant sandwich design. Instead, the British group built a simpler and more robust transducer in which the quartz mosaic was assembled between a steel plate and a mica sheet using no special bonding apart from Vaseline to exclude bubbles of air. Then the assembly was encapsulated with a waterproof and insulating mixture such as that used in cable construction (Figure 7). The amplifiers were initially obtained from France.

The system was operated initially at 75 kHz, but as Boyle pointed out in his report to the BIR, 'experiments have shown that thin sheets of quartz work well at all frequencies up to as high as have yet been tried, say, 120,000. They work "off resonance". i.e., by a "forced vibration", yet will work at any one frequency about as well as another.' [30]

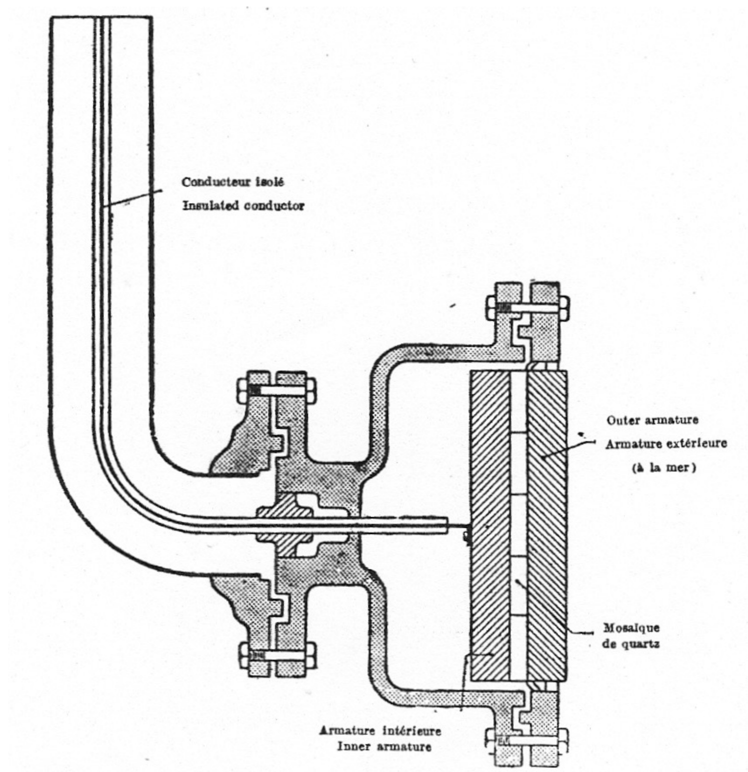

Fig 6. The Langevin-Florrison resonant quartz sandwich transducer.

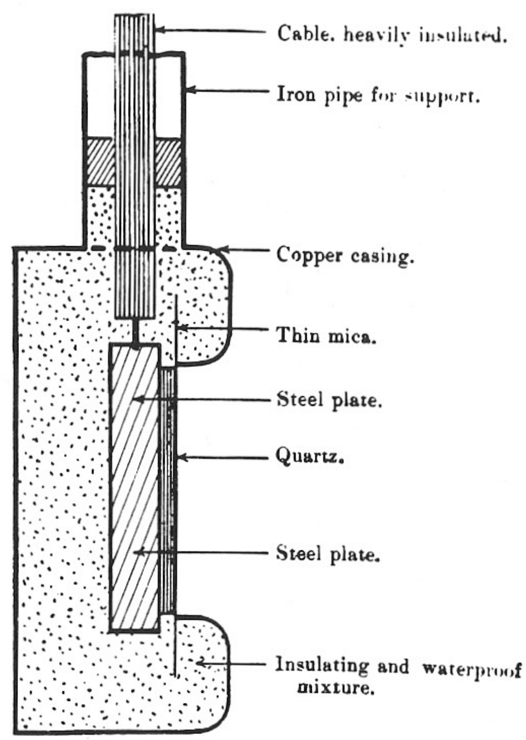

Fig 7. Boyle's broad-band encapsulated asdic transducer.

Langevin's theoretical five-fold gain from resonance would not be essential, provided sufficient attention was paid to coupling and amplification. The risk of water ingress during submersion would be eliminated, and it would be straightforward to alter the frequency of operation.

The initial arrangements were complete by October and by the end of 1917 Boyle's team had successfully transmitted between the ship *Heidra* and M.L.14, using their non-resonant transmitter to explore range at 45 kHz, 80 kHz and 127 kHz. Even at the highest frequency the range was nearly a mile, about 1.5 miles otherwise, including tests with a repaired mosaic transducer on loan from Langevin operating at 58 kHz.

It took until the February 1918 before the first signaling trials were commenced in France, when a signaling distance of 8 km was achieved. Operating in pulse-echo mode, clear echoes were obtained for the first time from a submarine. Boyle was not far behind. By March 1918, Boyle had successfully detected echoes from a submarine at a distance of 500 yards using the same transducer for transmission and for reception. By mid 1918, the French system had demonstrated submarine detection with a range extending occasionally to 1500 m.

The British stopped using the words quartz and supersonics. The term 'asdics' was introduced, for secrecy, an acronym apparently derived from 'Anti-Submarine-Detection-ics'. Quartz was known as 'asdevite'. The 'asdephone' was developed using quartz as a low-frequency listening device.

The war was almost over when both teams attended the Conference on Detection of Submarines by the Method of Supersonics in Paris in October 1918, to share their progress with each other and the four-man contingents from the USA and Italy. Although sea trials were underway, peace was declared before any navy used ultrasonic detection of submarines in action.

IV. ULTRASONICS AND SUPERSONICS 1920-1940

It was not until the 1939-45 war that Sonar re-emerged as an effective anti-submarine technology. The inter-war decades were characterized by progress in three areas of ultrasonics: the academic study of the ultrasonic acoustics, the exploration of possible applications of high-intensity ultrasound in engineering, chemistry and biology, and the development of underwater sensing for commercial and naval purposes. Each created knowledge and techniques that would later underpin the medical use of ultrasound, and the following sections outline some of the main developments

Robert Boyle declined an American offer to work there on ultrasound after the war, and failed to find an academic post in Britain. He returned to the University of Alberta, Canada, where he spent the next ten years working on the fundamental physics of ultrasound [31].

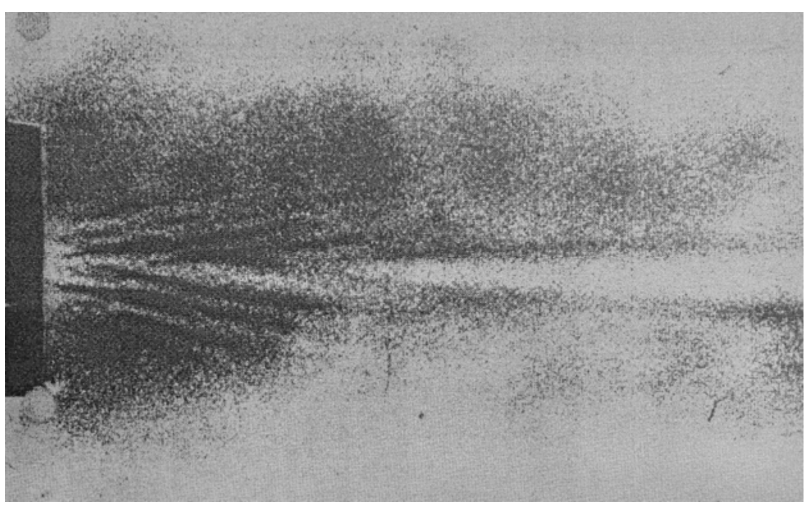

Fig 8. Boyle's dust images of the field of an ultrasound beam from a 178 kHz, 15.3 cm diameter circular source. [31] 1928.

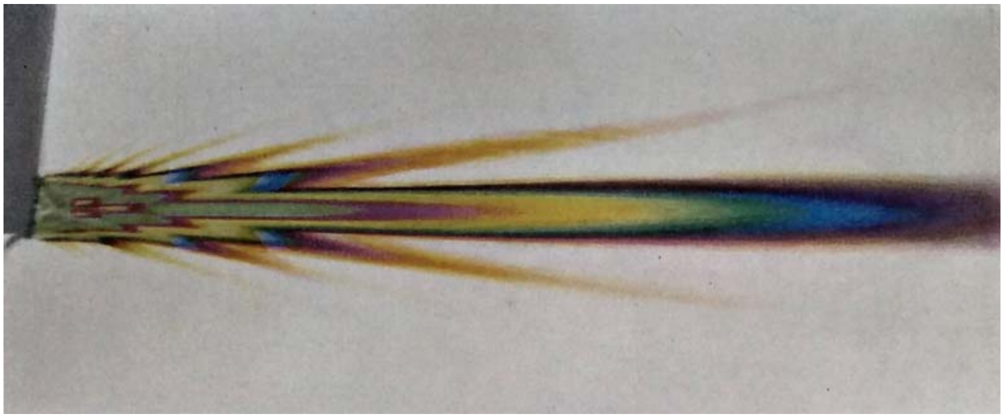

Fig 9. Beam from a source, 11 λ diameter, in C_6H_6. Hiedemann & Osterhammel 1938 [33].

His transducers were quartz mosaic slices bonded to metal plates and fully encapsulated with resin. Some were of the Langevin sandwich design, and some were piles of interleaved quartz and metal plates. In each case the resonance was determined by the overall thickness being λ/2. A simple detector hydrophone was built from a small capsule with mica sides connected to a stethoscope, which generated an audible tone at the pulse repetition frequency. Using fine dust powder, 'jostled from the regions of maximum to the regions of minimum energy density' whilst sinking onto a tray below the beam, he formed images of stationary waves, near-field and side-lobe diffraction patterns, two-beam interference and beam reflection (Figure 8) [32]. Within a decade, such crude approaches to beam visualization had been superseded, notably by the use of schlieren methods in the hands of Hiedemann and his co-workers in Cologne (Figure 9).

During the summer of 1928, Boyle visited several laboratories in Europe and recruited Donald Sproule from Hughes. Boyle and Sproule used radiation pressure to measure the relative axial and radial intensity profiles, using various designs of torsion pendulum. Using these as receivers, they measured transmission through thin layers, confirming that when the plate thickness was an integral number of half wavelengths nearly all the incident energy was transmitted [34]. Boyle also investigated velocity dispersion in liquids, concluding that any alterations of speed over the frequency range 30 kHz to 600 kHz were beyond the accuracy of his experimental measurement methods to observe.

In all, Boyle published twenty-five papers on the basic physics of ultrasound in the decade from 1922 to 1932. The first of these was on acoustic cavitation, and was probably the first academic paper to address this topic [35]. His interest arose from the association between bubble formation and the loss of sensitivity that he and Langevin had observed when trying to operate ultrasonic underwater systems at high power. Boyle correctly explained acoustic cavitation as the rupture of liquid during the rarefaction half-cycle, and also understood that this was less likely at higher frequencies. In a series of fundamental studies over the next few years he showed that there was a threshold for acoustic cavitation that increased with ambient pressure, and that it depended on the liquid, being lower in volatile hydrocarbons than in water. In studies into standing waves, he observed that bubbles migrated to nodes in stationary waves.

His studies on volatile liquids demonstrated that the released gas was largely air, and that liquids that had been so degassed showed a higher threshold for cavitation. He concluded that the liquid was not being ruptured and that cavitation was initiated as bubbles formed around dust particles. His specific conclusion was that cavitation 'tends to restrict the maximum intensity of energy transmissible'. Others investigated the increase in attenuation caused by cavitation [36]. Sonoluminescence was observed [37]. More relevant to the present topic is the association between cavitation and biological effects, and this will be addressed below.

Quartz transducers were by far the most common sources of ultrasound during the interwar years. Not only that, it seemed clear that the technology was not yet fully exploited. As upper frequencies increased towards 1 MHz and beyond, a potential upper limit was even being considered, estimated to be about 50 MHz for which a quartz slice only 0.054 mm would be required. Furthermore, it was shown that quartz could be shaped into a concave bowl, creating a focused ultrasound beam [38]. Both these ideas anticipated later developments in diagnostic imaging and focused surgery.

A. Non-linear acoustics

The narrative so far has largely concerned transducer engineering and the applications of ultrasound. The underlying acoustic principles, set out by Lord Rayleigh in 1877 in his *Theory of Sound*, had been transferred without modification to encompass the low ultrasonic spectrum, including beam structure, diffraction, refraction, scattering, and calculations of energy density and acoustic intensity. There was no need for further theory. One aspect of theoretical acoustics remained obscure, however. Acoustic wave transmission is an inherently non-linear process, both from local and cumulative effects. The resulting waveform distortion and associated harmonic generation was known, and had been analysed for a loss-less medium, but no progress had been made to include dissipation. In the 1930s a few steps were taken to resolve this difficult challenge. These formed the foundation on which, several decades later, an understanding of the relevance of non-linearity to medical ultrasound led very quickly to the successful commercial development of harmonic imaging.

In 1931, Fay published his analysis of the non-linear propagation of a periodic wave through a viscous gas [39]. His solution balanced the generation of harmonics as a result of non-linear propagation with their loss as a result of viscous absorption. The harmonic amplitudes for what is now called the Fay solution are $B_n = 2/n(1+\sigma)$ where $\sigma = x/x_s$ the distance with respect to the shock formation distance x_s [40]. Once an acoustic shock forms 'the wave forgets its origin' and the fundamental component approaches a value independent of the drive. This so-called acoustic saturation is of central importance in modern ultrasonic metrology and its use in safety standards. The explicit solution published by Fubini in 1935, is perhaps of less relevance because it is valid only for regions of weak non-linearity when $\sigma \leq 1.0$, that is before an acoustic shock has formed.

In Paris, Langevin's student Pierre Biquard (1901-1992), investigating the attenuation of ultrasound in liquids using a radiation force detector, observed an anomalous increase in transmission loss that was especially pronounced at high frequencies. He attributed this additional loss to the progressive formation of an acoustic shock, including a theoretical evaluation in his 1935 PhD thesis and in his extensive discussion of Langevin's 1923 lectures at the *College de France* [41] He gave an expression for the coefficient of non-linearity β that was very similar to the one used today, $\beta = 1 + B/2A$, in which A and B are the coefficients of a series expansion of the isentropic pressure-density relation.

B. Physical and chemical effects at very high intensities (supersonics)

A number of laboratory experimentalists started to explore the physical, chemical and biological effects of exposure to high intensity ultrasonic waves during the interwar decades. In the next sections, some of these effects will be described, with an emphasis on the biological effects which would underpin future considerations for the safety of ultrasound diagnostic devices, and its use for therapy and surgery.

When Langevin reported in Paris in October 1918, he had told the delegates that 'fish placed in the beam in the neighbourhood of the beam were killed immediately, and certain observers experienced a painful sensation on plunging the hand in this region'. Ten years later, the American physicist Robert Wood, recollected that 'when the frequency was adjusted for resonance the narrow beam of supersonic waves was shot across the tank causing the formation of millions of minute air bubbles and killing small fish that occasionally swam into the beam. If the hand was held in the water an almost insupportable pain was felt, which gave the impression that the bones were being heated.' [42]

Robert Williams Wood (1868-1955) [43] had spent two years in Berlin before settling in 1901 as professor of experimental physics at Johns Hopkins University. Well respected for his work in ultraviolet and infrared photography, his physics interests were wide ranging. By 1900 he had demonstrated how Toepler's 'schlieren' imaging could be used to visualise the propagation and reflection of the acoustic pulse caused by a spark, the precursor for modern ultrasonic pulsed schlieren imaging [44]. His physics career was built on excellent experimental science aided by a large dose of showmanship.

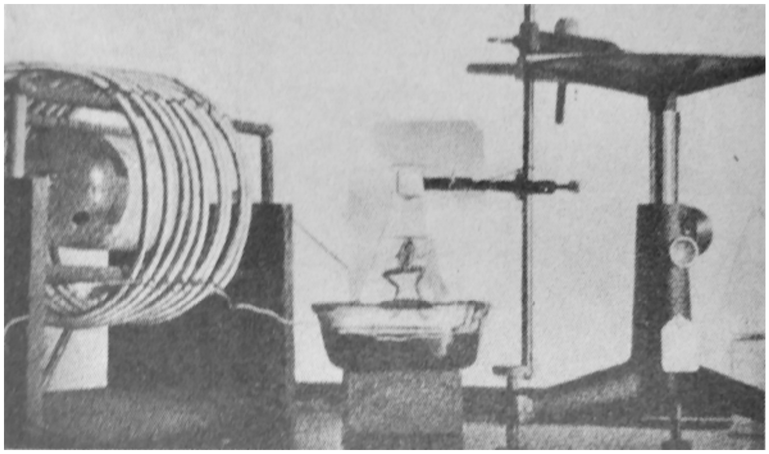

Fig 10. The coil and reaction chamber used by Wood and Loomis in their studies into the physical and biological effects of high-intensity ultrasound. [42]

Wood was known and respected in Europe. When he recalled that 'it was my good fortune during the war to be associated for a brief time with Prof. Langevin' …. on the submarine detection problem', he was probably there as an individual scientist, and not part of any official visit to Toulon during the war. He made no recorded contribution to the US submarine detection programme. After the war, Wood returned to his studies in optical spectroscopy, publishing a raft of papers and improving his own 40-foot diffraction grating, probably the largest in the world at that time, which was housed in his personal laboratory. It was here that he was visited by his old friend, the financier Alfred Lee Loomis, a Harvard law graduate who had become very rich by investing in utilities and was seeking a new interest. Loomis asked Wood if he could help him by financing a study 'which required more money than the budget of the Physics Department could supply', no doubt assuming this would probably be an even larger optical instrument of some sort [45].

Instead, Wood suggested they should explore 'supersonics'. In 1926, with Loomis' money, they bought a 2 kW oscillator, originally designed for an induction furnace, added capacitative tuning to operate between 100 kHz and 500 kHz and an output transformer, to give a maximum potential across the quartz plate of 50 kV (Figure 10). No subtlety was applied to transducer design: 'The quartz plates were circular discs, and when in operation, one of them rested on a disc of sheet lead at the bottom of a dish of transformer oil. The other electrode consisted of a disc of very thin sheet brass resting on the upper surface of the quartz. ' [46]

The results were spectacular. Their paper, Loomis' first in any scientific journal, was deliberately eye-catching [47]. The purpose was to give maximum publicity to the newly established 'Alfred Lee Loomis Laboratory, Tuxedo, N.Y.', from which the paper heading announced that it was 'Communication No 1'. Publication, in September 1927, was not in America, but in the prestigious *London, Edinburgh, and Dublin Philosophical Magazine.* With few exceptions the paper was descriptive, and low on explanatory science. Much was made of the high radiation forces generated at the oil/air interface, and its chaotic disruption. Variation in output due to acoustic loading was noted, but without serious analysis. Extreme temperature increases were deliberately established. Glass was melted. A fine glass needle caused a severe burn that took a long time to heal. Aggregation and emulsification was observed. Mists were generated. Stationary waves were generated in tubes. The only graph showed the change in measured velocity with frequency in glass rods and disks.

This was Wood's only contribution to ultrasonics, apart from his later monograph 'Supersonics' (1939). (The term supersonics was introduced to mean high-intensity ultrasound). For Loomis, things were different. This paper launched his new career as a scientist. His strategy was to invite established scientists to work with him in the private laboratory that he built in his new home in the fashionable New York district of Tuxedo Park. Funding their equipment and attaching himself to their work, he became co-author on their papers. Simultaneous publication on both sides of the Atlantic extended the publication list and the publicity. Having equipped Tuxedo Park to carry out ultrasonic experiments, several scientists took Wood's place to work there. Loomis published on the chemical effects of ultrasound with William Richards from Princetown. With the physicist J C Hubbard, a colleague of Woods at Johns Hopkins, he developed an interferometer for the measurement of sound speed in liquids, solutions and liquid mixtures. Hubbard published four papers with Loomis on its design and use and subsequent papers during the 1930s [48,49]. In particular, they published accurate values for the temperature and salinity-dependence of sound speed, which were important when tissue-equivalent phantoms were first being designed for the calibration of medical ultrasound scanners.

C. Ultrasonic biological effects

The first paper from Tuxedo Park included 'biological effects' in its title. It established an association between ultrasound and lethality that coloured later attitudes to its safe use. Wood called ultrasound 'death rays'. 'We worked together, killing fish and mice, and trying to find out how and why they were killed, that is whether the waves destroyed tissue or acted on the nerves or what'. In order to help them understand what was going on, they recruited Edmund Newton Harvey, professor of zoology at Princeton, sometimes working with his wife Ethel [50]. Emphasis was on the role of cavitation in cell lysis, at first using Wood's high power system and then a 75 W system more suited to microscopic studies, operating at 1.25 MHz and 2.25 MHz [51]. The results from Tuxedo Park sparked interest around the world in the effects of ultrasound, with attention focused on the mechanisms causing cell destruction [52].

Frank Lloyd Hopwood (1884-1954) was another physicist who had been introduced to ultrasound during the war, and who was studying the biological effects at the same time as Loomis set up his laboratory. Professor of physics at St Bartholomew's Hospital Medical School (Bart's) in London, Hopwood was one of the earliest physicists in Britain to devote his career to medicine, appointed as demonstrator in physics there in 1906. During the war he had worked on directional hydrophones to listen for submarine noise, introducing an air film to make them uni-directional [53,54]. The hydrophones were being tested at Parkeston Quay, Harwich, during the time that Boyle was developing asdics there. Hopwood heard about the biological effects observed in Toulon and 'determined that when circumstances permitted he would investigate the matter'.

Hopwood carried out similar studies as those by Harvey, giving an overview in 1931 in which he referred to work carried out 'during the past few years' [55,56]. In common with all early experimentalists, he used an X-cut quartz plate. This was clamped to a lead substrate with a light copper foil as the second electrode, immersed in oil. He used a 3 kW oscillator. Intensity was estimated using radiation pressure. His biological results were similar to those reported by Harvey, lysis of cells, plant cell destruction and alterations in nerve and cardiac muscle action. (Figure 11). Given the purpose of the present article, the important distinction between Harvey's and Hopwood's work was in the placing of the laboratory: in the one case in a personal laboratory designed to publicize private investment in science, and the other, a physics laboratory that was embedded in the work of a medical school. Hopwood was president of the British Institute of Radiology in 1932-33. In his presidential address he included ultrasound in a review of new medical technologies, alongside 100 MHz diathermy, infrared photography, soft x-ray microscopy and MV x-ray therapy. Nevertheless, his ultrasound studies dwelt on its destructive power, and he failed to interest his clinical colleagues in ultrasound as a therapeutic agent [57].

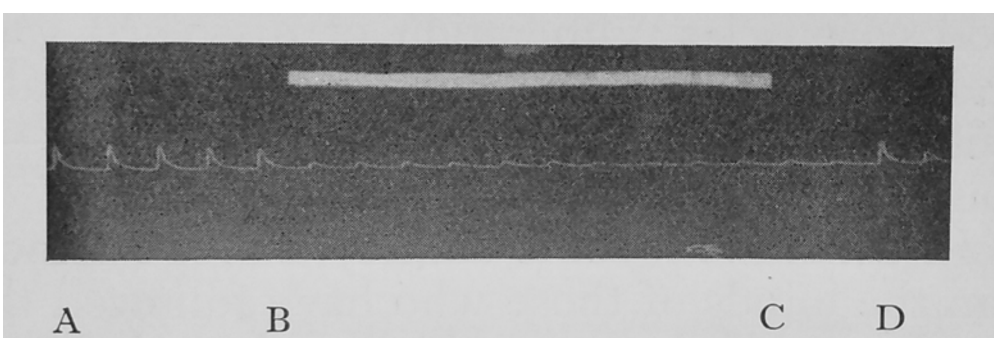

Fig 11. Inhibition of nerve conduction due to ultrasound exposure from B to C. (Hopwood, 1931). [55]

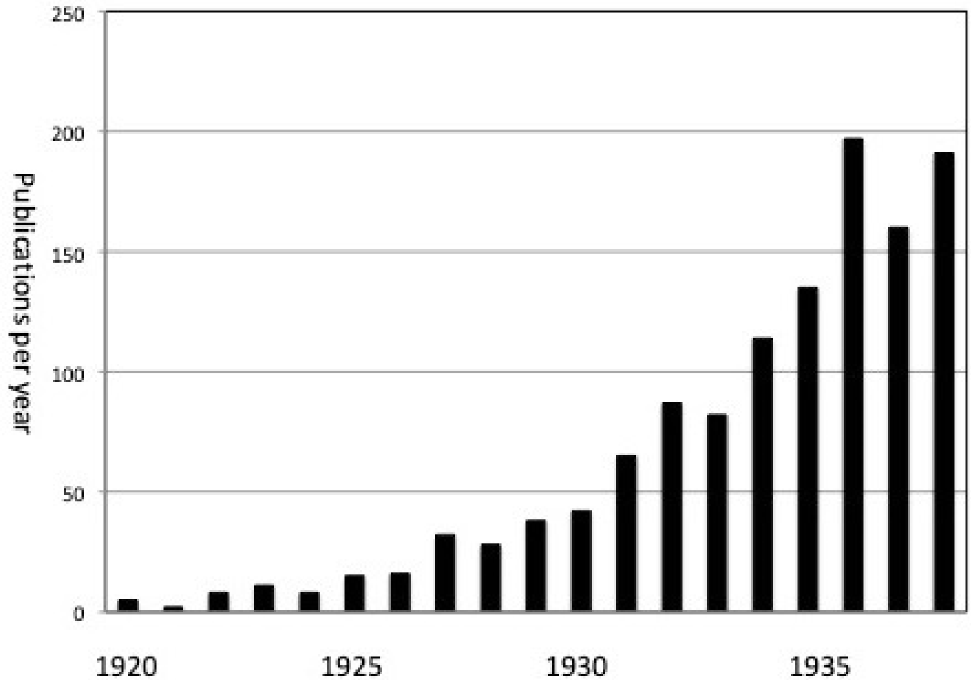

Fig 12. The growth in papers on ultrasound and associated topics from 1920 to 1938. Hiedemann 1939. [58]

Biological studies formed only one component of the growth in ultrasonic acoustics during the 1930s. (Figure 12). These years also saw rapid developments in acoustic metrology, including new devices using radiation pressure, thermal sensors and optical methods for beam visualization. There were several remarkable studies of optical diffraction and secondary interference, gaining insights into the structure of anisotropic solids. Ultrasound spectroscopy gave insights into molecular structure through studies of absorption and velocity dispersion in liquids and gasses. Physico-chemical techniques, for dispersion, coagulation, emulsion formation and degassing, were widely reported. It is not appropriate to review most of these developments, except where they form the basis for future medical applications.

V. Ultrasonic therapy

Serious studies into the bioeffects of ultrasound emerged, notably in France. The Romanian physicist Néda Marinesco had moved to Paris, where he completed his doctorate on molecular biophysics under Jean Perrin in 1927. After working on the biological effects of electric fields, he set up an ultrasound laboratory at the *Intitut de Biologie Physico-chemique* [59]. His main results were published in two parts in 1937 [60]. He constructed his two systems from second-hand and scrap equipment, one at 2 kW and the other operating at 250 W. His quartz transducers were from 2 mm to 6.5 mm in thickness, operated at their fundamental resonance of between 428 kHz and 1.43 MHz. He reported results on the destruction of micro-organisms, preparation of colloids, photochemical reactions and, most impressively, on explosive reactions. He concluded that water from the Seine could be made safe to drink after 60 m insonation at 1 kW, but it would not be practicable 'because a litre of Seine water made drinkable in this way would cost 0.25 Fr, obviously overpriced '.

Another physicist, working like Hopwood in a medical faculty, started to investigate the therapeutic potential offered by ultrasound. André Dognon (1900-1970) deserves more recognition for his role in the development of medical physics and medical ultrasound. His *Précis de physico-chimie biologique et médicale* (1929) established a reputation early in his career, when he was associate (agrégé) professor in physics at the Faculty of Medicine in Paris under the lead of André Strohl. Dognon would eventually be appointed as professor of medical physics on Strohl's retirement.

Writing in 1953, he recalled 'When, around 1930, I discussed with E. and H. Biancani the study of ultrasound as regards its biological actions, it was hardly known except by the few specialists who dealt with underwater sounding, or acoustics physicists, to whom it offered new possibilities for theoretical developments or experimental studies [61].

Dognon was offered a laboratory at the hospital *Hôtel-Dieu*, and it was here, with Elio and Hugo Biancani, that he explored the bio-medical effects of ultrasound. The Biancani brothers were already using several physical agents in their medical practice, including light, infrared and ultraviolet therapies, and were interested to explore with Dognon what ultrasound had to offer. Their work appeared in three main publications between 1935 and 1938 [62,63,64]. Unlike the other early investigators who largely built their own equipment, Dognon sensibly used the expertise that had been developed in France for underwater echo-sounding in the company SCAM, using Florisson's advice, and a generator that the company made available to them.

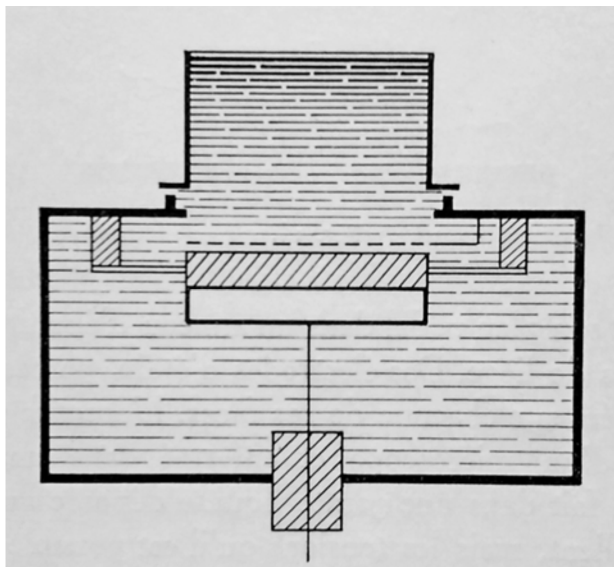

Fig 13. The French SCAM physiotherapy transducer (c.1933).

All previous investigators had immersed the quartz transducer in the insonated liquid. Instead, Dognon used Florisson's patented design, a stand-alone 'hand-held' transducer [65] (Figure 13). 'The original idea was to be able to project an ultrasonic beam in any position onto a given surface or into any container.' The quartz plate, 6 cm diameter, resonance 250 kHz, was held by three wires, with a hollow metal case applied to the back face, which served as one electrode. The upper, ground, electrode was a thin perforated sheet of aluminium. The surrounding metal box was fitted with extension tubes of various lengths, closed by a metallic or organic membrane, and the whole container filled with oil or petroleum. The maximum power was about 450 W. It was this transducer that they used for most of their experiments.

The second change was a practical approach to metrology. They argued that cavitation caused radiation pressure measurements to be unstable so, for the first time, investigated calorimetry. In a rather crude thermal sensor, they filled a glass tube with paraffin oil, and the temperature increase generated in the oil during exposure was measured with a small mercury thermometer. Whilst such an arrangement is of no value for absolute intensity, he was able to identify resonant conditions for maximum output, and was even able to plot an approximate beam profile.

Using this and other exposure arrangements they reproduced many of the phenomena observed by Harvey, Marinesco and Hopwood, although working with a somewhat lower power. Like them, Dognon observed that cavitation and mechanical agitation were the most obvious effects. But, whilst the others were aware of heating, Dognon investigated the temperature rise more thoroughly. He compared the temperature rise after a standard exposure time (10 s or 30 s) in small volumes of various liquids and soft tissues.

'Examination of these figures leads us to important remarks as to the possible mechanism of the biological action of ultrasound. The basic facts are as follows. There are substances whose heating always remains insignificant: water, gelatine gels or proteins, whatever their viscosity or cohesion. On the other hand, a whole series of other bodies, of a fatty or lipoid nature, are heated, sometimes strongly, the magnitude being linked in part to their low conductivity and specific heat, but also to their high absorption. ….. It is natural to think that the considerable heating of fatty or lipid tissues must play an important role in the genesis of physiological disturbances caused by ultrasound of great intensity. On the other hand, it is interesting to see, contrary to what one might have expected, from the theoretical evaluation of the absorption coefficient, the small influence of viscosity.'

These remarks, with their focus on absorption and heating, concern the biological action in whole tissues. Cavitation, central to the interpretation of in-vitro results, is not mentioned. Dognon considered that ultrasonic heating was the therapeutic agent [66]. 'The ultrasonic projector that we have described was precisely intended to transmit energy to the surface of the skin, and we know that this energy is transmitted very well inside the tissues.'

In fact, the idea of using ultrasound for therapy pre-dated Dognon, who noted that 'the original patents of MM Langevin and Chilowsky on piezoelectric transmitters already envisaged a possible application of vibrating baths to therapy.' Langevin had said the same to his audience during his ultrasound lectures at the Collége du France in the 1920's. The physicist Frithiof (Fred) Wolfers (1890-1971), recalled this in his review '*Les ultra-sons et la biology*' written in 1930 [67]. Much in his fifty-page treatise is drawn from notes for Langevin's course, and Wolfers noted his thanks for entrusting him with them. In a brief section on the possibility of therapy he wrote: '… it does not seem impossible, *a priori*, to obtain interesting therapeutic effects. With relatively low frequencies and low or moderate energies, and by applying the source directly to the surface of the body, it would be possible to adjust the wavelength and pressure amplitude, and therefore the pressure gradient at each point of the body. We would create in this way a kind of "internal massage" …. the creation of a real "phonotherapy" '

In a footnote, Wolfers added that this was not his idea, noting that it had been already suggested by Langevin and his student Léon Brillouin. This reference may well relate to Brillouin's 1925 patent for a method of 'indirect vibratory massage' [68].

Unsurprisingly, a few laboratories around the world started to investigate whether ultrasound had the potential to treat cancer. Studies were reported from Europe, Japan and the USA, but the results were equivocal, whether used alone or in conjunction with radiotherapy [69].

It was left to the German physicist Reimar Pohlman (1907-1978) to establish the use of ultrasound for therapy. Pohlman was a physics and chemistry graduate from Heidelberg and Berlin, and gained his PhD in 1932 [70]. In 1935, now assistant at the Physikalisch-Chemischen Institut of the University of Berlin, he had commenced research on air-borne ultrasound. A year later he published his first patent for a 'Device for the detection of defects in solid and liquid bodies by means of sound, in particular ultrasound waves' [71]. In 1939 he proposed a means for imaging the ultrasound wave that became known as the Pohlman cell [72].

He later described how, in 1938, he commenced work in ultrasound therapy [73]. He specifically rejected the high intensity approach to cancer therapy being explored at the time. Instead, he proposed that ultrasound at lower intensities could be used to stimulate healing through a combination of thermal and mechanical processes [74]. His first experiments were designed to select the most appropriate frequency to use. 'In connection with these investigations, the question of the absorption of ultrasound in human tissues, its frequency dependence, and the depth of penetration of the radiation was of major significance'. From measurements at 800 kHz and at 2.4 MHz, he concluded that he would gain greater tissue penetration at the lower of these frequencies, which he selected for the clinical evaluation. Attenuation at 800 kHz, expressed as half-value thickness for intensity, was 6.8 cm for adipose tissue, and 3.6 cm for muscle. For mixed muscle and fat, the half-value thickness at 2.4 MHz was 1.5 cm, compared with 4.9 cm at 800 kHz. He found no difference between the attenuation of tissue of adults and children, within an error limit of about 10%. He confirmed Dognon's observations that the frequency dependence of the absorption coefficient did not follow the square-law dependence expected from classical theory of viscous loss, concluding incorrectly that the lower-than-expected absorption at the higher frequency resulted from the absence of cavitation [75].

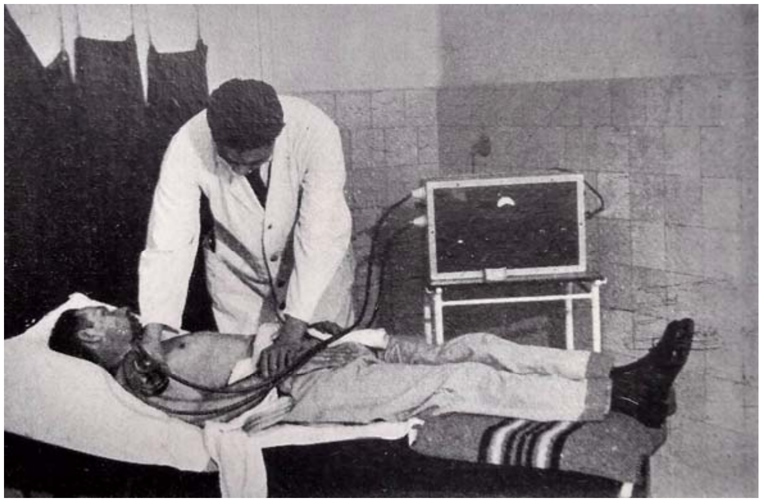

Fig 14. Clinical ultrasound therapy. Martin Luther Hospital Berlin. 1938. [73]

The first clinical trials of his ultrasound therapy were carried out before the end of 1938 in the Martin Luther Hospital Berlin-Grunewald. (Figure 14). His clinical colleagues were E Parow-Souchon and R Richter. Favourable results were reported for some neurological and neuro-muscular disorders [76].

Pohlmann described his first crude prototype transducer, and their initial approach to dosimetry:

'The radiation head was made of glass and had a thin, ultrasound-permeable membrane. This caused a certain burning feeling, and at that time the dosage was carried out in the primitive way that when the treatment head was put on locally, the intensity was regulated so that the resulting warm pain was just at the limit of tolerance. Measurements showed that this corresponds to an intensity of around 4-5 W cm^{-2}. If one stroked the body part to be treated with the massage head adjusted in this way, applying light pressure, the patient had a subjective feeling of pleasant warming, and a slight hyperaemia was noticed, which resulted partly from the warming and partly from the intense vibration.'

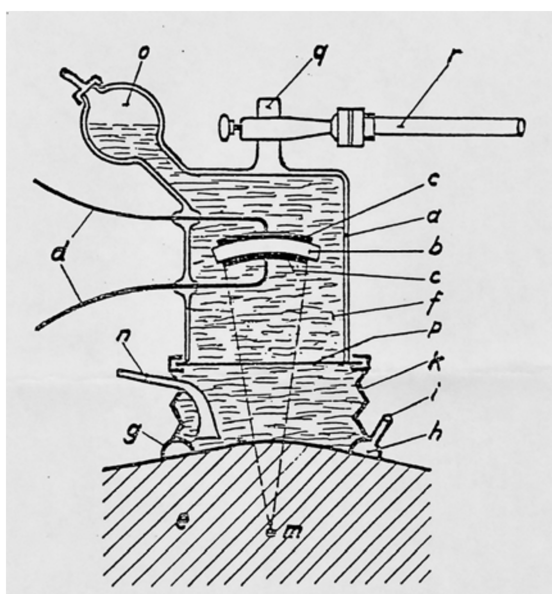

Fig 15. Siemens patented focused bowl transducer for treatment. 1935. [77].

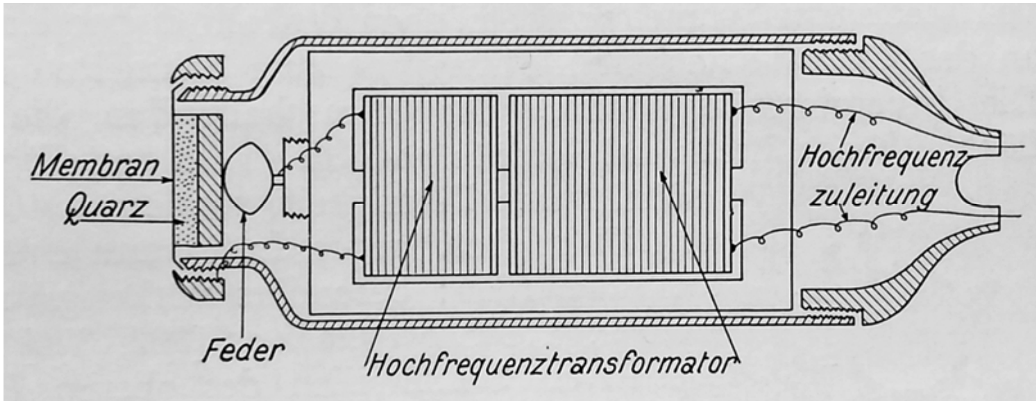

Fig 16. Ultrasound transducer for therapy. 800 kHz. Pohlmann 1939.

At the same time that Pohlmann was starting to investigate ultrasound therapy there was also interest in ultrasound treatment at Siemens-Reiniger-Werke in Berlin. In December 1935, Siemens had filed a patent for a water-coupled focused transducer for treating patients [77] (Figure 15). At this date, the bowl transducer would have had to be made from several angled and shaped crystal pieces [78]. The department responsible for this work was led by the physicist and Nobel Laureate Gustav Hertz. He had been taken under the protection of Siemens in 1934 by being appointed as overall director of Research Laboratory II, where he could continue his work in isotope separation. At the end of the war, Hertz joined a pact with other German scientists and moved to the USSR.

In 1939, following their successful clinical demonstration, Pohlmann was recruited by Siemens to take responsibility for the ultrasound laboratory in Hertz' department. Access to improved engineering support helped him to create a better transducer (Figure 16). A 4 cm^2 quartz plate was mounted in oil between a spring and an outer membrane, and a step-up transformer was built inside the transducer housing. He slightly reduced the overall maximum power to 15 W. In use, the head was massaged into the skin, using paraffin oil as a coupling material, or an anaesthetic treatment cream containing bee venom or forapin. During the war years, Siemens started to supply equipment to other clinics in Germany, who reported their early results. Pohlmann himself investigated enhanced transcutaneous transport of topical medication, with Florstedt at the Charité, Berlin [79]. Other work was reported from Berlin, Wolfsburg and Erlangen.

Siemens-Reiniger-Werke partially relocated to the comparative safety of Erlangen in 1943. Pohlman was joined by Theodor Hueter, and together they extended the measurements of the frequency-dependence of tissue attenuation up to 4.5 MHz, concluding that the absorption coefficient showed a broadly linear frequency dependence [80]. Pohlman explored alternative means to measure transmission loss, including optical [81] and thermoelectric methods [82]. He left Siemens in 1948 to move to Switzerland, and Hueter moved to the USA in 1950, to take up a position at the Massachusetts Institute of Technology.

Civilian economic reconstruction after the war favoured the growth of ultrasound therapy. Pohlmann could report 75 publications during 1949 on ultrasound therapy, and listed seventeen companies manufacturing therapeutic ultrasound equipment, twelve in Germany, four Austrian and one in France [73]. In the same year, André Denier identified three more manufacturers in France, one in Belgium and four manufacturers in the USA. The operating frequencies lay between 800 kHz and 3 MHz, and manufacturers limited the maximum intensity to between 2 W cm^{-2} and 10 W $^{-2}$. One manufacturer, Dr. Born of Frankfurt, offered pulsed operation at ratios of 1:5, 1:10 and 1:20. Ultrasound therapy had become fully established.


N° 2572.
21 Juillet 1923.
LA NATURE
REVUE DES SCIENCES ET DE LEURS APPLICATIONS A L'ART ET A L'INDUSTRIE
LES ULTRA-SONS
SOMMAIRE :
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MASSON ET Cie, Editeurs.
120, boulevard Saint-Germain, Paris.
LE NUMÉRO : 1 franc.

Fig 17. Echo-sounding in the popular press 1923.

VI. Underwater sensing and sonar

The underwater use of ultrasound, successfully demonstrated during the first war, continued to develop once hostilities ended in 1918. Langevin worked with the electrical engineer Charles-Louis Florisson to develop directional ultrasonic depth-sounding equipment, operating at 40 kHz [83] (Figure 17). The first sounding took place off Nice in October 1920. This approach had distinct advantages over other non-directional echo-sounding systems that were being concurrently developed that operated in the audible range of frequencies. Langevin licensed his patent portfolio to *Société de condensation et d'applications méchaniques* (SCAM), and ultrasonic echo-sounding became a commercial success. He shared some of the income associated with his patents with Marie Curie's daughters, Irene and Eve, and with Jacques Curie, whose PhD had originally described the quartz piézo-électrique [84].

The new challenges were comparable to those facing the later designers of medical ultrasonic equipment. There was interference between the transmit pulse and echoes from close targets. Using a bistable preamplifier to switch from transmission to reception, Langevin reported that he could distinguish an echo from a target as close as 1 m [26]. A means of continuous recording was needed. Langevin's collaboration with P.A.D. Marti of the French Hydrographic service gave rise to a continuous depth recorder, plotting the change in echo with time as the boat moved. The '*Sondeur Ultra-sonore Langevin-Florrison-Marti'* was widely installed on merchant and passenger ships by SCAM. In Britain, Henry Hughes and Sons produced their first recording echo-sounder for the Admiralty in 1923, with a recorder designed by their chief engineer Donald Sproule [85]. Characterization of the sea-bottom from the nature of the echo, whether sand, mud or clay, was also investigated at this time, a technique revisited in the 1970s for tissue characterization [86].

Naval applications generated interest in transducers other than quartz. There were two early piezoelectric alternatives. In tourmaline the polar axis coincides with the optical axis, so it was suitable as a hydrophone receiver for studies of the transmission of high-amplitude pressure waves from underwater explosives, where the three-dimension strains could result in charge cancellation in quartz [87]. The second alternative was X-cut Rochelle salt in which the piezoelectric effect is considerable greater than either quartz or tourmaline [88]. Rochelle salt was used as the receiver for the prototype US echolocation system before the end of the war, but it was a decade before a reliable method of manufacture was established. By 1940, Rochelle salt had become the preferred material used by the US Navy for its echo-ranging and submarine detection equipment. Moreover, off-resonance response meant that it could operate over a range of frequencies [89]. Later in the war, experimental assemblies of ammonium dihydrogen phosphate (ADP) crystals were tested, some capable of operating up to 100 kHz. By contrast, the British navy retained the pre-war resonant quartz transducers, largely operating at frequencies below 20 kHz.

A more robust alternative arose from the development of magnetostrictive transducers [90]. Magnetostrictive generation of sound results from periodic extension and contraction of a rod or tube of ferromagnetic material, typically a nickel-iron alloy, when placed in an oscillating magnetic field parallel to its length. The main advantages over quartz were cheapness and sturdiness. However, even at the lower frequencies where they were mostly used, magnetostrictive receiver sensitivity was about 40 dB below quartz, and, in transmission, they had to be driven at higher electrical powers to achieve the same acoustic output. In addition, eddy currents restricted the practical upper frequency limit to about 300 kHz. Whilst there were early ultrasound therapy units that used magnetostrictive transducers, such as the 175 kHz Atlas-Werke ‘Supersonic’, they were unusual [91]. No medical diagnostic systems used magnetostrictive transducers.

In all operational sonar and asdics systems, scanning was achieved by mounting the transducer on a rotating arm, and repetitive scanning carried out every 5˚, sweeping 90˚ each side of the direction of travel. Such a procedure required about 2.5 minutes for a complete sweep. By the end of the war, experimental switched scanning sonars had been developed. The Harvard Underwater Sound Laboratory system used a cylindrical array, flooding the whole 360° field during a 30 ms transmission (Figure 18). On reception, a small number of elements were selected, and rapidly switched in sequence to achieve a scan repetition rate of 30 Hz, ‘introducing suitable phase displacement for making these elements into a directional hydrophone’ [92]. The echoes were presented on a cathode ray screen.

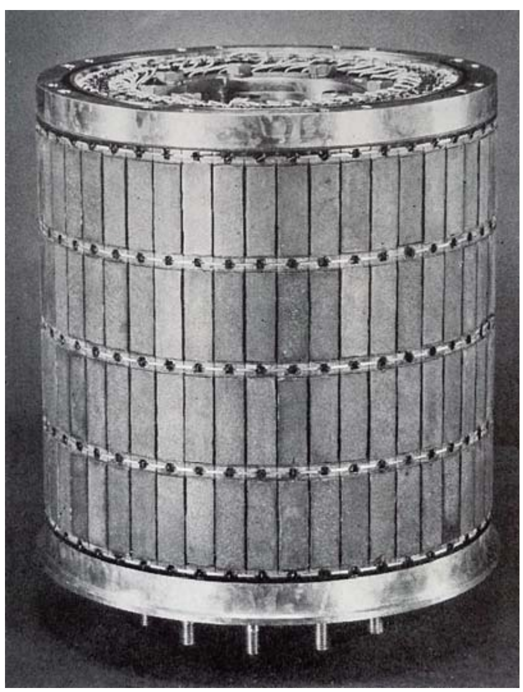

Fig 18. US Navy Scanning Sonar XQHA transducer with rubber cover removed. 1945. [92]

The frequency shift in the echo, caused by relative movement between the ship and the target, the Doppler shift, was also used by Sonar operators, who were trained to listen for any change in pitch of the 'pings' and interpret this in terms of speed and direction of the target. Doppler-shift would become an integral part of medical ultrasound. Thus, by the end of the war, underwater pulse-echo techniques were not only well-established in practice but also the transducer, driver and detection electronics and display systems underpinning this use were well advanced. This included array beam forming on reception, and echo display using cathode ray oscilloscopes.

VII. The first four books on ultrasound

The end of the first wave of expansion in ultrasound was marked by the publication of four specialist books on this new part of acoustics within the space of four years, from 1937 to 1941. Two were in Germany one in France and the fourth in the USA.

Ludwig Bergman's *Ultraschall* was published by VDI-Verlag in Berlin in July 1937 [90]. Bergmann (1898-1959) had obtained a PhD from Geissen University in 1921 and then worked for Telefunken and at the University of Marburg. He joined Clemens Schaefer at the University of Warsaw in 1927, with whom he compiled the standard physics textbook, *Bergmann-Schaefer Lehrbuch der Experimentalphysik.* His first publications in ultrasound were in 1932, working on the piezoelectric properties of quartz and opto-acoustic effects. In 1939, he was appointed director of the physics department of the Technical University, and honorary professor at the University of Warsaw. After the war, he worked for Leitz and returned to Hesse as honorary professor at Giessen.

Bergmann's book emphasized the practical side of ultrasound, with many details of experimental studies and industrial applications. Indeed, the author gives credit to several German manufacturers for assistance with illustrations and other details. Following its publication, there was immediate interest in the USA and, the following year, Bergmann's book appeared in English translation by H Stafford Hatfield, published by John Wiley, with an additional section on ultrasonics in television. A second edition was published in 1946.

The second German book was *Grundlagen und Ergebnisse der Ultraschallforschung* (Basics and results of ultrasound research) by Egon Hiedemann (1900-1969) [58]. It included a greater emphasis on the fundamental physics and laboratory experiments, and included a remarkable 1346 cited references. Hiedemann had gained his PhD from Göttingen, before returning to Cologne where he was elected associate professor in 1931. Like Bergmann, he applied optical techniques to investigate ultrasonic fields, and was one of the earliest investigators into non-linear propagation effects. Hiedemann moved to the USA after the war, eventually becoming head of physics at Michigan State University.

Robert Wood's 150-page book '*Supersonics, the science of inaudible sounds',* was based on three lectures given in the Colver Lecture programme at Brown University in 1937 [42]. It covered broadly the same material as Bergmann but in perhaps less detail, with greater emphasis on the work from the Loomis laboratory.

The last of the early books on ultrasound was *Les ultrasons*, by Pierre Biquard [93]. It was very different from the others both in scope and intended audience. First published on 11 August 1941 in occupied Paris, it was volume 21 in the series of short paperbacks called *'Que sais-je'*. The series aim was to present an accessible introduction to a subject for a lay reader, written by an expert, within a small format 128-page book. The opening sentence, "14 avril 1912. – A bord du grand paquebot de la "White Star Line" tout le monde est heureux', (On board the great liner of the "White Star Line" everyone is happy), introducing the sinking of the Titanic as the trigger for the development of ultrasound, sets the tone of this well-illustrated, concise scientific and technical description of ultrasound. It undoubtedly reached a far wider audience than the other three books, the 9th edition still in print in 1983.

The circumstances of these two men, Biquard and Hiedemann, in 1941 could not have been in greater contrast. The German had just been appointed as professor and head of applied physics at the new Reichsuniversität at Strasbourg, an appointment that was made even though he was not a party member, a common requirement for new academic appointments at that time.

Meanwhile, Biquard was a fugitive in Lyons. A confirmed pacifist, Biquard had been secretary of the Paris section of the *Comité de vigilance des intellectuels antifascistes,* formed under Langevin's lead in 1935. By this stage in his life, Langevin had given priority to politics above science. As the left-wing British scientist JD Bernal wrote in his preface to Biquard's biography of Langevin, 'I have always remembered his dictum …. that if we did not do our scientific work someone else would, but if we neglected the political work, there would soon be no science' [94].

Biquard took part in the agitation caused by the arrest and imprisonment of Langevin after the capitulation of France. He was dismissed from his job as a scientist in the French Navy in December 1940, under the racial law. Under threat of arrest, Biquard went underground in Lyons where he spent rest of the occupation, participating in the French resistance movement. Which is why, when the wartime editions of his book were published, it was under the name of Francis Draveil, one of several cover names that Biquard used during the war.

VIII. Ultrasonic testing by through-transmission

During the pre-war growth of ultrasonics, interest developed in its use for testing materials. Whilst there were occasional proposals that reflected waves could be used, these innovations largely centred on methods using transmitted ultrasound.

When Mühlhäuser was granted his 1931 German patent for ultrasonic methods for testing materials he included proposals for testing by transmission or by reflection [95] (Figure 19). In both cases, two transducers were used, and inhomogeneity within a sample was inferred by reduced transmission between them. The Russian physicist Sergei Sokolov was working at the Lenin Electrotechnical Institute in Leningrad in 1928 when he proposed his through-transmission technique for flaw detection in metals. At first he measured the transmitted intensity using light diffraction. By 1935 he had proposed the first image projection method using optical investigation of the surface displacement of oil [96]. A prototype was manufactured by VEB Jenoptik, Jena, for testing large sheet panels. By 1937 he had showed that the charge distribution induced on a quartz receiver could be scanned using the electron beam in an evacuated cathode ray tube, the so-called Sokolov Tube. Instruments working at 4 MHz based on this principle were later constructed by Jenoptik and proposed for medical applications [97].

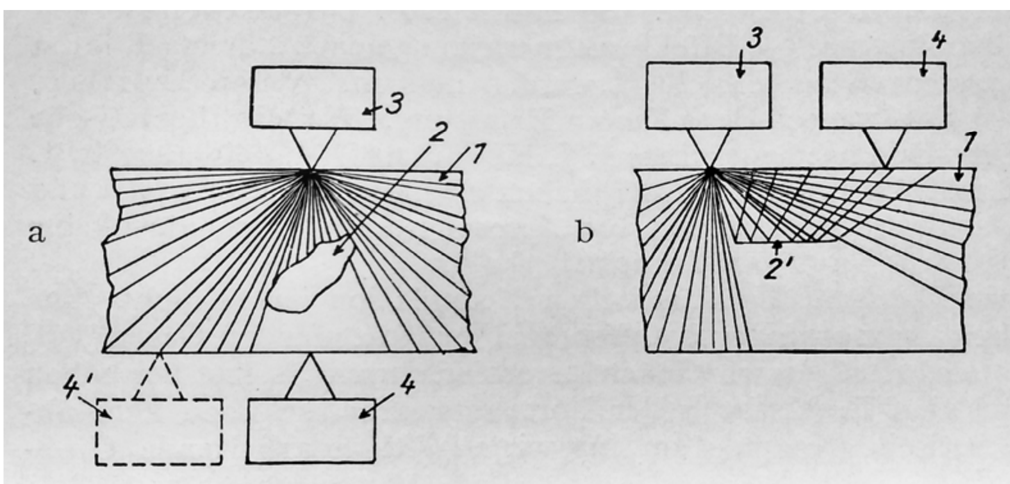

Fig 19. Ultrasonic materials testing by transmission (a) and reflection (b). 3: transmitter: 4,4`: receiver. Mühlhäuser 1931. [94]

A. Medical applications of transmission techniques

Drawing on these industrial developments, there were a number of attempts to exploit through-transmission of ultrasound for medical diagnosis. But, as Dognon said in his 1953 monograph on ultrasound ‘Obviously, it is urgent to apply methods already rich in results in the industrial field to the study of the human body. Unfortunately, the situation is much less favourable, because the body, the organs, and even most of the tissues are roughly heterogeneous in terms of their acoustic properties. The air, often present, constitutes, in the form of bubbles or thin sheets, interfaces of total reflection. Other more or less marked reflections occur at each zone of contact between tissues of different density or compressibility’ [98].

André Dénier’s simple homemade ‘ultra-sonoscope’, announced in 1946, was one example, a device that recorded the insertion loss through a tissue sample or organ [99]. In one application, the transmitter was placed on the trochanter and a vibration was picked up at the heel, perhaps as a means to diagnose fracture [100]. Another novel study by Wolf-Dieter Keidel, working in the Medical Physics laboratory at the University of Erlangen, used 60 kHz trans-thoracic transmission to investigate the heart [101]. The transmitted amplitude tracked the cyclic change in heart volume generating an ‘ultrasonocardiogram’. (Figure 20). But, as Dognon pointed out ‘truth be told, we have simpler and more precise methods for this’.

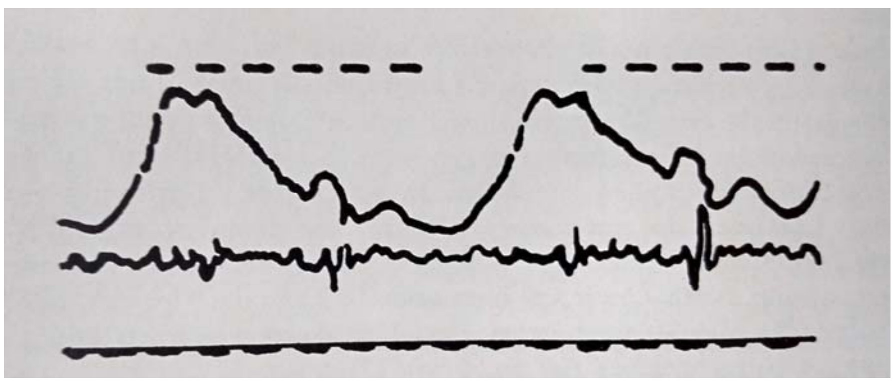

Fig 20. Keidel’s ultrasound cardiogram by transmission (upper trace). The lower trace shows the heart sounds. (1950). [101]

The most well-known failure from this period of transmission studies was due to the Austrian physician Karl Dussik, amplified by the Massachusetts Institute of Technology (MIT). Dussik’s tentative first paper on ultrasound was published in 1942 [102]. His first paper concerned transmission imaging of the heart [103] and the second on the brain [104]. The skull was immersed in a box containing water, and opposing quartz transducers were moved in a raster to scan the whole organ. The intensity of the reception modulated the brightness of a lamp and recorded photographically. Dussik’s work came to the attention of the American physicist Richard Bolt, who gained funding to construct a similar instrument in Bolt’s newly opened Ultrasonics Laboratory at MIT using improved electronics and replacing quartz transducers with barium titanate. Theodor Hueter was recruited from Siemens. Before leaving Erlangen in 1950, Hueter had the opportunity to try out pulse-echo methods with animal tissues but found the resulting echo signals difficult to interpret. He was easily persuaded to take part in a transmission imaging project instead, accepting the parallel with the x-radiography.

In reality, the images were swamped by diffraction artefacts, and much identified as pathology was noise. Refraction and diffraction limit the information in the transmitted beam, and attenuation limits the frequency that can be used and hence the resolution that can be achieved. Critical independent comment soon followed [105]. While the project was high in visual impact because images were produced it was never destined to open significant new avenues for clinical diagnosis. The episode had one positive outcome, however. In 1955, Hueter and Bolt published ‘*Sonics. Techniques for the use of sound and ultrasound in engineering and science’* in which their knowledge and skills from both sides of the Atlantic combined into a single seminal text-book [106]. Dussik’s heroic failure did not prevent him from being identified by some as ’The Father of Ultrasonic Diagnosis’ [107].

IX. Ferro-electric ceramic transducers

During the first thirty years, X-cut quartz, X-cut Rochelle salt and ADP had been the only piezoelectric sources of ultrasound. The invention of ferromagnetic ceramic piezoelectric materials created a revolution in ultrasound transducer technology. In 1947 this innovation was announced by three separate groups, notably by Warren Mason at Bell Telephone Laboratories [108,109]. All crystals have a second-order electrostrictive effect in which distortion occurs which is proportional to the square of the electric displacement. This ferroelectric effect is large in Rochelle salt, in potassium dihydrogen phosphate and in barium titanate, over a particular temperature range. The Curie temperature for barium titanate is 120 °C, above which ferroelectric properties are lost. In order to exploit this ferro-electric effect in a polycrystalline ceramic it is necessary to align the domains using a DC polarising voltage at a temperature above its Curie temperature [110]. It was soon also discovered that the introduction of small amounts of lead titanate into the ceramic caused a considerable increase in the thickness expansion, exceeding that found in magnetostrictive materials. It also prevented the decay of the ferroelectricity after the poling voltage had been removed. Further work on alternative ceramic mixtures led eventually to the dominance of the various forms of lead zirconate titanate ferroelectric ceramics that were used exclusively in the first development of medical ultrasonics. As Mason observed, a definite advantage of the ceramic transducer is that it can be moulded, leading to the possibility of producing focusing radiators of any size or shape. Unlike the situation with shaped transducers cut from pieces of crystal, this type of transducer can be made equally efficient for all points on the surface. Some of the weakly focussed ceramic transducers that were central to the achievement of good lateral resolution in medical imaging were shaped in this way, whilst focussed bowls have been essential to the development of ultrasound surgery.

X. Ultrasonic echo testing

On 27 May 1940, Floyd Firestone (1898-1986) filed for his first USA ultrasound patent ‘Flaw detecting device and measuring instrument’ [111]. From the Departments of Physics and Engineering Research at the University of Michigan, he stated that his invention ‘pertains to a device for detecting the presence of inhomogeneities of density or elasticity in materials’ and that it ‘may also be used for the measurement of dimensions of objects, and is particularly useful where one of the faces to which the measurement extends is inaccessible.‘

Firestone was well established as an acoustician, and had been editor-in-chief of the Journal of the Acoustic Society of America since 1939. He would become president of the ASA in 1943. Nevertheless, his previous publications had been limited to the audible spectrum, concentrating particularly on electro-mechanical analogies [112]. It was rare for papers in JASA, or at the ASA meetings, to include anything on ultrasound. The paper given by Hanfried Ludloff from Cornell University at the 23rd meeting of the ASA, 29-30 April 1940 in Washington, ‘Ultrasound and Elasticity’, may well have sparked Firestone’s interest. Ludloff was a recent German émigré who had worked on acoustic surface waves in Bergmann’s ultrasound laboratory in Warsaw before the war [113]. His paper at the 1940 meeting was unusual, not only because it was about ultrasound, but also because it concerned its transmission though solids in order to test their material properties [114]. His method, using optical interference caused by ultrasonic wave gratings to uniquely determine the elasticity and symmetry of an object, could not be applied easily to real-world testing. But it could well have been the trigger that led Firestone to invent a more practical ultrasound testing device.

Firestone was conscious that if any new testing regime was to be universally applicable, it needed to detect flaws very close to the surface, as well as those at depth. This led him initially to reject the pulse-echo method used for underwater detection. Instead, his method was a pulsed version of the method proposed by Mühlhäuser. It used two transducers, which are shown, in the patent, one on the end of the sample under test and the other on its side. He proposed using ‘perhaps 1,000,000 cycles per second’ although he identifies a lower bound of 15 kHz and notes that thinner crystals might generate ‘10 or even 50 megacycles’. The pulse repetition frequency would be about 100 Hz and the pulse length one cycle or less, a specification at odds with the resonant crystal transducers then available. The receiver amplifier could be tuned or broadband ‘from 1000 to 10,000,000 cycles per second’. Two transducers, piezoelectric or magnetostrictive, would be used, one for transmission and the other for reception, allowing them to be placed at any relative positions. The patent does not address the difficult question of coupling, a concern addressed by earlier workers on through-transmission testing.

When the patent was granted on April 21 1942, the USA was at war. It was the first of five patents filed by Firestone, as his understanding of the practical challenges of ultrasonic testing developed. The second, filed two years after the first on 29 June 1942, was the first to specify a single transducer acting as both transmitter and receiver [115] (Figure 21). Firestone had by then negotiated with industry, by then being 'assignor to United Aircraft Corporation East Hartford Conn'. This patent includes a control on the number of cycles in the pulse, and a receiver amplifier that 'shall within approximately a millionth of a second recover its sensitivity so that it may be sensitive to the feeble voltage trains generated by the crystal when feeble trains are reflected back to it from flaws distant only a fraction of an inch from the sending point'. To approach his aspiration to reduce the pulse to 'as short as half a cycle', he damped the quartz resonance with a backing block of Bakelite. In due course he patented a stand-off to resolve the problem of near-field detection [116].

Development of the 'Mark 1 Supersonic Reflectoscope' continued in Michigan during the war, the construction and testing carried out by Julian Frederick. By 1945, Firestone had transferred his industrial partnership to Sperry Products Inc of Hoboken, New Jersey. Commercial development of the Sperry Reflectoscope Mark 2 used a single 5 MHz quartz transducer in pulse-echo mode, the transducer driven by 1 μs pulses, and a repetition frequency of 60 Hz, the values suggested in the second patent. Transducer resonance caused the acoustic pulse to lengthen to about 5 μs. Oil was used for coupling [117,118]. The first academic paper includes 'reflectograms', oscilloscope traces both as RF and demodulated (A mode) pulse, typically including five sequential sweeps on one screen. Results showing the evaluation of laminations, welds, grain size and wall thickness were given.

The electronic design of the Mark II Reflectoscope was primarily due to the engineer Benson Carlin (1915-1996). Carlin had taught radio engineering for the Signal Corps at Monmouth until July 1943 and, after a brief period in the Radiation Laboratory at MIT, joined Sperry Products Corporation as a research and product engineer. Later, he played an important role in the introduction of medical ultrasound, recalling that Firestone once pointed the transducer onto his leg and remarked, 'See, you might be able to find things in the body' [119].

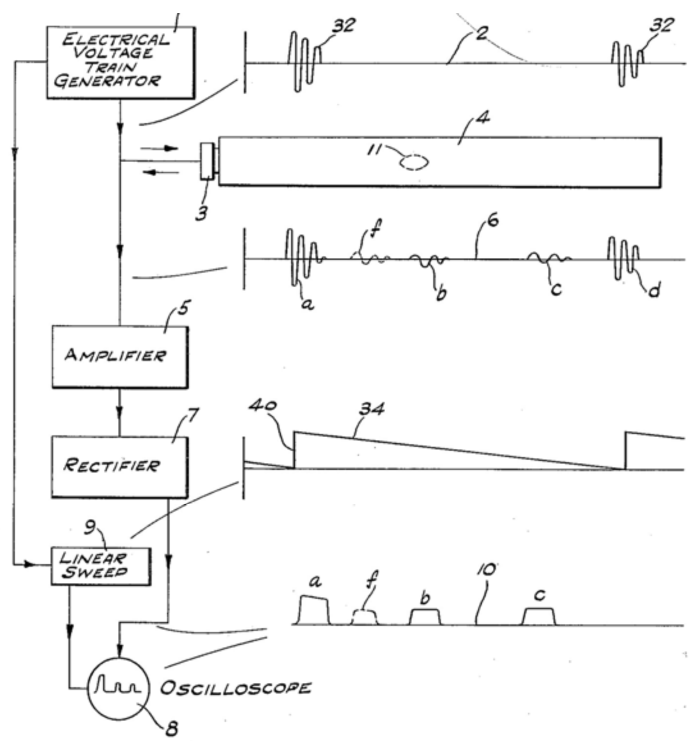

Fig 21. Block diagram from Firestone's pulse-echo patent. 1942

It is not surprising to find other initiatives at this time. In the United Kingdom, a Hairline Cracks Sub-Committee was set up, reporting to the Alloy Steels Research Committee of the Iron and Steel Research Council. The chairman was the eminent metallurgist Cecil H Desch FRS, recently retired from academic life. In November 1939 it was decided to investigate the possibility of employing "supersonic waves" for industrial purposes. Desch knew of the pre-war development of asdic systems for the Royal Navy and invited the company responsible for this development, Henry Hughes, to assist in his investigations. As a result, much of the experimental work for the sub-committee was carried out in the Hughes Research Division, under the direction of Donald Sproule, now returned from Canada. The initial experiments used well-established transmission techniques, but were found to be very limited in sensitivity. It was only in 1942 that Sproule began to investigate pulse-echo techniques, using, as he put it, 'echo-sounder principles to sounding in a solid sea'. By July 1943 Sproule and his colleagues were able to demonstrate a working prototype, using separate transmit and receive transducers with overlapping beams. (Figure 22) They used two heavily damped quartz transducers about 1 mm thick and 2 cm diameter, angled downwards into the sample to be tested. Heavy damping allowed the transducer, with a nominal resonant frequency about 2.5 MHz, to be operated at subharmonic frequencies down to 625 kHz. The 300 V pulse was generated by the rapid discharge of a capacitor through a thyratron. Once the war ended, details were released and Hughes produced the Mk I ultrasonic metal flaw detector [120]. The use of two transducers allowed flaws to be detected as close as 1 cm from the surface.

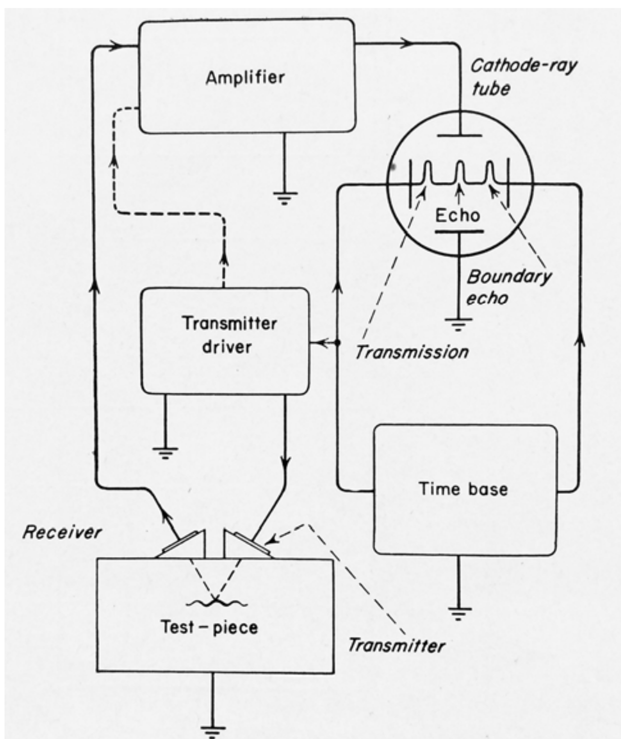

Fig 22. Block diagram from the Hughes pulse-echo system. 1943.

Carlin was well placed to record the technical details of developments at this time. In his book 'Ultrasonics", published in 1949, he identified the enabling technologies that underpinned these new developments in ultrasound [121]. Carlin recognised the similarity between short-range materials testing using ultrasonic pulses and the techniques used in sonar and in radar, noting that both work best if the transmitter and receiver are identical. This challenges the ability to detect objects close to the transmitter. For radar, pulse lengths were of the order of 1 μs, in contrast to pulse lengths up to 100 ms for sonar. Pulse circuits, capable of electronically shaping very short MHz pulses, had been developed for radar. RF pulses had been generated in a number of ways, using gas valves or thyratron switches, or switched circuits with high-vacuum valves. Cathode-ray oscilloscopes had been available before the war, but it was not until 1946 that the triggered-sweep oscilloscope, developed for radar, became commercially available from Tektronix. Mapping of echo location had been previously developed for both sonar and radar although at this stage materials testing with ultrasound was restricted to A-mode. Marker circuits enabled time reference points to be displayed, and hence a distance calibration to be set up. Broadband receivers were required to achieve good resolution. Carlin was very clear about the debt paid to radar technologies in the early development of ultrasonic testing.

Other engineers with radar and sonar experience were encouraged by their companies to explore new applications, including ultrasound applied to medicine. RP McLoughlin was working as an engineer in the Argentinian subsidiary of RCA Victor when he started to explore the possibility of foreign body location in the body using pulse-echo methods, together with the physician GN Guastivino, They published their prototype results at 1.5 MHz using the acronym LUPAM (Localizador ultrasonoscopico para aplicaciones medicas) in 1949. The paper included an A-mode oscilloscope trace showing reflections from a bone and from a stone embedded in an excised kidney. Notably, it also suggests that echo position could use the PPI (plan position indicator) presentation developed for radar, with a rough sketch showing how a medical image might appear. [122]

In France, Florisson continued his interest in medical applications, contributing to the first issue of *UIltraschall in der medizin* in 1949 [123]. Josef Krautkrämer in Cologne and Karl Deutsch in Wuppertal both started investigating pulse-echo materials testing in 1949, offering commercial pulsed test equipment a year later. Siemens soon followed with the Ultraschall-Impulsgerät, released in 1952. It was a development of this device that was borrowed, in 1953, by Gustav Hertz' son Hellmuth, working with Inge Edler in Malmö, to initiate ultrasound echo technology for cardiology.

But, when Pohlman reviewed the status of ultrasound in 1950, he could report only that 'The echo method is a very promising approach for diagnostics, but it is also not yet fully developed. So far nothing has become known about practical applications'. Practical diagnostic ultrasound was still in the future.

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